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AUTOMATION AND OPTIMIZATION OF THE DESIGN PARAMETERS IN TACTICAL MILITARY PIPELINE SYSTEMS

A Thesis in

Petroleum and Natural Gas Engineering

by

Robert Michael Frick

Submitted in Partial Fulfillment
of the Requirements
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ABSTRACT

Tactical military petroleum pipeline systems will play a vital role in any future conflict due to an increased consumption of petroleum products by our combined Armed Forces. The tactical pipelines must be rapidly constructed and highly mobile to keep pace with the constantly changing battle zone. Currently, the design of these pipeline systems is time consuming and inefficient, which may cause shortages of fuel and pipeline components at the front lines. Therefore, a need for a computer program that will both automate and optimize the pipeline design process is quite apparent.

These design needs are satisfied by developing a software package using Advanced Basic (IBM DOS) programming language and made to run on an IBM-compatible personal computer. The program affords the user the options of either finding the optimum pump station locations for a proposed pipeline or calculating the maximum operating pressures for an existing pipeline. By automating the design procedure, a field engineer can vary the pipeline length, diameter, roughness, viscosity, gravity, flow rate, pump station pressure, or terrain profile and see how it affects the other parameters in just a few seconds.

The design process was optimized by implementing a weighting scheme based on the volume percent of each fuel in the pipeline at any given time. The weighting scheme was tested and compared with current military design examples and showed a savings in the number of pump stations ranging from 7.7 to 23.1%. As the volume percent of the lighter fuels in the pipeline increases, so also does the net savings of pump stations.

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NOMENCLATURE

A	=	cross sectional area, ft^2
°API	=	API gravity, dimensionless
d	=	diameter of line, ft
f	=	friction factor, dimensionless
f_D	=	Darcy friction factor, dimensionless
g_c	=	gravitational force constant, ft/sec^2
H	=	head, ft
H_f	=	head loss due to friction, ft
L	=	length of line, ft
Le	=	equivalent length, ft
NPMSH	=	net positive minimum suction head, ft
P	=	pressure, psi
Q	=	flow rate, bbl/hr
r	=	radius, ft
Re	=	Reynold's number, dimensionless
sp gr	=	specific gravity, dimensionless
T	=	temperature, F
t	=	time, t
V	=	specific volume, ft^3/lb
v	=	velocity, ft/sec
X	=	position of elevation, ft
Δ	=	difference between two numbers

ε	=	absolute roughness, ft
ε/D	=	relative roughness, dimensionless
μ	=	viscosity, lb/ft-sec
π	=	pi, 3.1415926
ρ	=	density, lb/ft^3

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The author wishes to express his appreciation to the Department of Defense and the United States Air Force for providing the opportunity to pursue his graduate studies and for covering all financial considerations incurred. Thanks are also in order for Dr. Michael A. Adewumi, thesis advisor, for his wisdom and positive outlook on all facets of the research process.

Chapter 1

INTRODUCTION

Background Information

Increased mechanization and the concept of mobile warfare dictate that in future conflicts there will be a considerable increase in the consumption of petroleum products by our Armed Forces. In the event of a large-scale military operation during conventional type warfare, fuel will be supplied to troops in bulk quantities up to or near the front lines through tactical pipelines. These coupled pipelines can be rapidly constructed and are capable of providing sufficient fuel for several mechanized divisions or forward air bases.

The most important element in the actual design of a tactical military pipeline system is that of pump station spacing. Basically, the spacing is determined by the hydraulic design, that is, by the head loss in the pipe for reasons of friction and elevation when the line is operating at the normal capacity for which it is designed. It is important that all stations are in balance hydraulically. This is to say that each station in the system must have the same work load to perform. The design factors which determine station spacing include: (1) topographic features of the pipeline route; (2) type and properties of the design fuel; (3) the required suction pressures, available head capacity, and other operating characteristics of the pumping units; (4) the friction head losses for the selected size of pipe.

Since pipes and pump stations are precious commodities during hostile conflicts, each tactical pipeline system is designed to deliver multiple products. The types of fuels most likely to be transported by military pipelines are aviation

gasoline, motor gasoline, diesel fuel, jet fuel, and occasionally oils such as kerosene. The current practice is to select the heaviest fuel to be transported as the "pipeline design fuel." This method of selection is rather inefficient because more pump stations will be used than are necessary. This is especially crucial in combat situations when the possibility of equipment supply interruptions is always imminent. There is a need to evolve an optimal design of the pump station spacing to account for the fact that the pipeline carries multiple products, each of which differs in transport properties.

Statement of the Problem

Currently, field engineers must use field manuals and engineering kits to manually determine the pump station spacing required for a proposed tactical military pipeline. This process can take from several hours to a day to complete. If hostile action dictates the relocation of the pipeline, the field engineer must again perform manual calculations which will delay the pipeline being moved to a new location. This delay could cause shortages of fuel at the front lines which could ultimately affect the outcome of a battle.

It is therefore the primary objective of this research to create a software package that will automate the design of military pipelines and give the field engineer greater flexibility in meeting existing and future fuel demands. The software generated is to be written in Advanced Basic (IBM[1] Disk Operating System [DOS]) programming language and made to run on an IBM-compatible personal computer.

[1]IBM is a registered trademark of International Business Machines, Inc.

The program will also incorporate the most current hydraulic design equations and be interactive and user-friendly.

The second objective of this research is to optimize the design process by developing and implementing an appropriate weighting scheme based on the volume percent of each fuel in the pipeline at any given time. By minimizing the number of pump stations per pipeline, the field engineer will be better able to allocate his battlefield resources.

Chapter 2

STRATEGIC IMPORTANCE OF MILITARY PIPELINES

The immense quantities of liquid fuels required in modern warfare make up over half the total tonnage of supplies moving into theaters of operations. Moving this tonnage within the theater by means of pipelines has both advantages and disadvantages, however, the advantages weigh heavily towards pipeline transportation over other comparable means.

Installations and Facilities

A military petroleum bulk supply and distribution system in a theater of operations is usually composed of a marine terminal, pumping stations, trunk pipelines, branch pipelines, intermediate and pipehead storage, tank farm complexes, bulk reduction points, and communication circuits. Figure 2.1 illustrates a typical military petroleum bulk supply and distribution system in schematic form.

In an overseas theater, a military petroleum bulk supply and distribution system begins at a seaside port where fuel is unloaded from tankers. The use of existing wharfs simplifies the job of tanker unloading. When wharfs are not available, other means have to be provided. These include jetties, ship moorings, and submarine pipelines. This operation is depicted in the ship-to-shore installation in figure 2.1.

From the tanker unloading facilities (submarine, jetty, or dockside), the fuel is pumped forward to terminal storage facilities. These facilities are composed of a

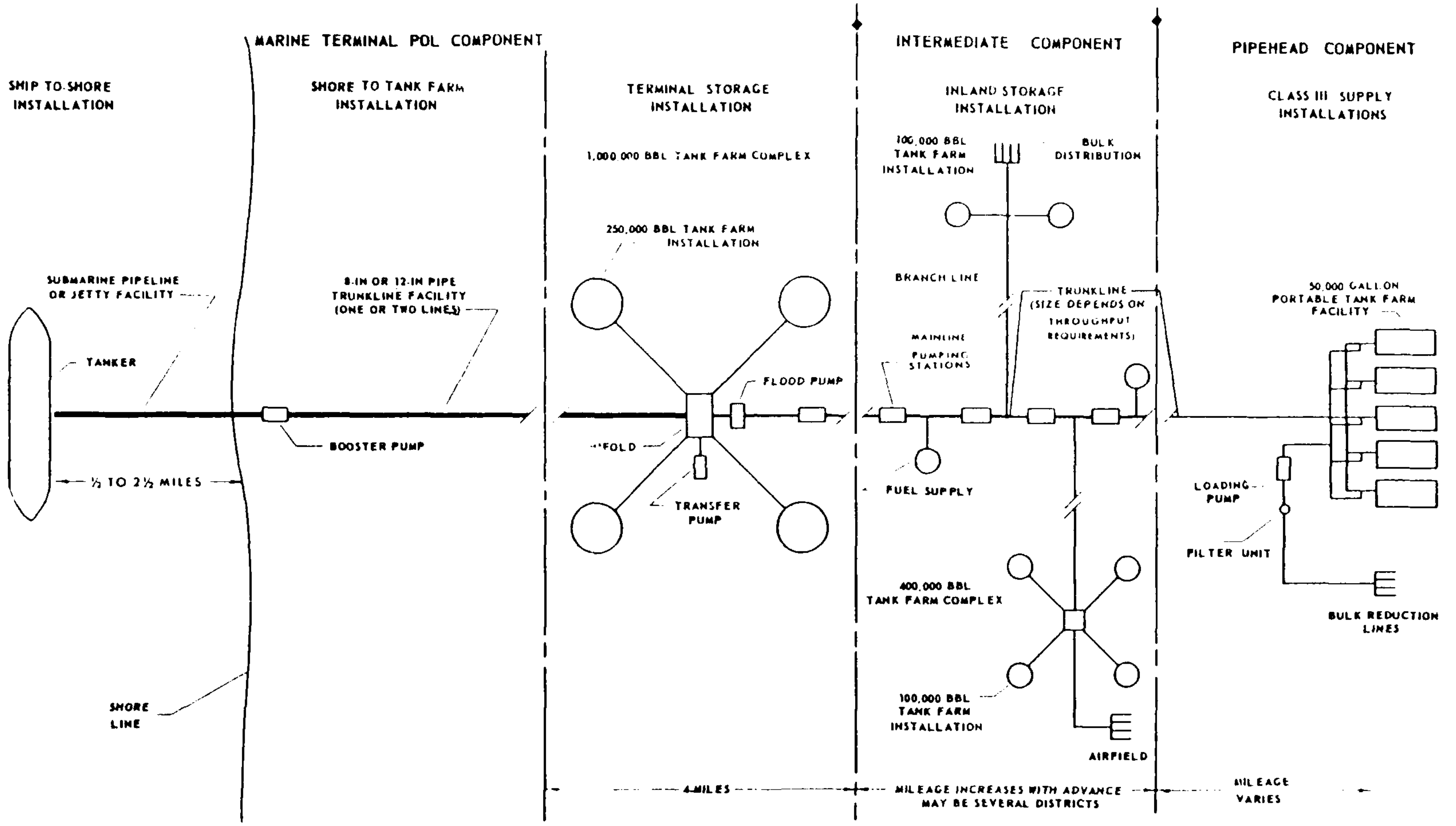

Figure 2.1 Schematic diagram of a petroleum bulk supply and distribution system in a theater of operations. (Source: Department of the Army, 1969.)

single 200,000 barrel tank farm, or 400,000 - 1,000,000 barrel major tank farm complexes. All storage tanks in a farm or major complex are interconnected by pipelines manifolded so that one to four petroleum products can be moved into, out of, and between tanks in accordance with scheduled utilization requirements. Normally, only one 12-inch main trunk pipeline is required to supply a 200,000 barrel marine terminal; however, two lines or more are needed for terminals having a capacity of 400,000 barrels or more. This part of the fuel supply operation is shown in the marine terminal POL component in figure 2.1.

From the marine terminal, the trunkline is extended forward and reduced in size to follow the course of the battle. The intermediate and pipehead component sections of figure 2.1 illustrate this part of the petroleum distribution system. Branch lines may be connected to the trunkline to serve airfields and other large consumers. These branch pipelines are constructed with pipe sizes dependent on throughput requirements. The pipehead terminal supporting a field army or forward air base may move forward as often as every 2 or 3 days depending on the progress of the battle. These tactical pipelines must be highly mobile and put into operation as quickly as possible. Therefore, this part of the fuel supply process is the primary area of interest to this research.

Advantages of Pipelines

The use of pipelines to move vast quantities of petroleum within a theater of operation has the following advantages:

1. The burden of fuel transportation is removed from rail and road networks already loaded with the movement of troops, equipment, and other supplies

essential to military operations.

2. The use of pipelines releases a large number of vehicles and personnel for other essential supply activities. Furthermore, adverse weather conditions do not present as many serious problems to pipeline operation as they do to road and rail transport.

3. Pipelines can be constructed over adverse terrain where construction of major roads or railroads would be extremely costly in manpower and time.

4. Pipelines and their pumping stations are relatively immune to successful air attack. They can be located to take advantage of natural cover, and if damaged, they can be quickly repaired or replaced.

Disadvantages of Pipelines

Among the military disadvantages encountered in the use of pipelines are the following:

1. In occupied enemy territory, the pipeline is vulnerable to disruption by saboteurs and guerrilla warfare specialists. Even in friendly territory, there are tampering and pilfering hazards from civilians. This disadvantage can be partially overcome by burying the pipeline. Also, if the pipeline is well designed, with sufficient tankage at intermediate points, line breaks will not necessarily cause complete shutdown of the line.

2. Marine-terminal installations and tank farm complexes make attractive targets for enemy air and missile attack. Camouflage, concealment, dispersion, dummy and decoy installations, and fire and damage control methods reduce the damage risk from such attack.

3. In a rapidly changing situation, the rate of pipeline construction may lag behind the rate of combat advance. The rate of construction may vary from 2 to 10 miles per day, depending on the terrain features encountered and the state of training of the engineering troops employed in construction.

Chapter 3

REVIEW OF PIPELINE DESIGN LITERATURE

Past Developments

The oil pipeline industry was launched in 1865, six years after Col. Edwin Drake drilled America's first oil well near Titusville, Pennsylvania. An acquaintance of Drake's by the name of Samuel Van Syckel built a pipeline five miles long to transport the new crude oil. The pipeline pumped approximately 80 barrels of oil an hour through a two-inch wrought-iron line, lap-welded with screw threaded joints, from Pithole City to the Oil Creek railroad station in Oil City, Pennsylvania [Association of Oil Pipelines, 1987]. This first pipeline project was quite different from the 76,000 barrel per hour rate of the Trans Alaska pipeline that went into operation in 1977. An accomplishment of this magnitude could only have been realized by an ever increasing knowledge of pipeline design.

Steady-State Liquid Flow Equations

For Newtonian fluids such as all military fuels, thermodynamics and friction factor calculations can be combined to produce a working equation. Bernoulli [cited by Streeter, 1961] used the first and second laws of thermodynamics, along with the assumptions that flow is isothermal and adiabatic, to produce the following equation:

$$\int V\,dP + (X_2 - X_1) + \frac{v^2_2 - v^2_1}{2\,g_c} = -\frac{2\,f\,L\,v^2}{g_c\,d} \qquad (3.1)$$

Where:

$\int V\,dP$ is the energy loss due to the volumetric behavior of the transported fluid

$(X_2 - X_1)$ is the potential energy change

$\frac{(v_2^2 - v_1^2)}{(2\,g_c)}$ is the kinetic energy change

$\frac{2\,f\,L\,v^2}{(g_c\,d)}$ is the friction loss

Equation 3.1 applies for any line section where work is not done on or by the flowing fluid. These various terms in equation 3.1 represent all of the energy terms involved in a line of length "L" and diameter "d."

If the liquid is assumed to be incompressible and flowing in a constant diameter line, then

$$\int V\,dP = V\,(P_2 - P_1), \quad \text{and} \quad KE = 0.$$

With all these assumptions, equation 3.1 becomes

$$V\,(P_2 - P_1) = -\frac{2\,f\,L\,v^2}{g_c\,d} - \Delta X \tag{3.2}$$

Equation 3.2 is the usual working equation for the flow of a Newtonian liquid. As written, each term possesses head units, with "V" being specific volume, the reciprocal of density $(\frac{1}{\rho})$. If one makes this substitution for "V" in equation 3.2 and then multiplies each term by density, the result is

$$\Delta P = (P_2 - P_1) = - \frac{2 f L v^2 \rho}{g_c d} - \rho \Delta X \tag{3.3}$$

Each term now possesses pressure units.

The energy balance required for calculation of fluid flow behavior involves calculation of "lost work," the total irreversible energy loss to the pipe wall that is unavailable to move the fluid or perform any other action. The friction factor, f, is the empirical term used to assess the numerical value of these irreversible losses. The work done in overcoming friction through a distance, dL, is proportional to the surface in contact with the fluid, approximately proportional to the square of velocity and proportional to the fluid density. By letting H_f represent the total head loss due to friction, the equation may be written

$$dH_f = f (dL) \pi d (\frac{v^2}{2 g_c}) \rho \tag{3.4}$$

The weight of fluid in any section of pipe is the product of the section length, dL, the cross-sectional area and the fluid density. Any frictional work would be represented by the frictional resistance over a distance dL. Combining these contributions to "losses" yields

$$dH_f = \frac{f (dL) \pi d (\frac{v^2}{2 g_c}) \rho \, dL}{\frac{\pi}{4} (d^2) \rho (dL)} \tag{3.5}$$

Simplifying and integrating gives

$$H_f = \frac{2 f L v^2}{g_c d} \tag{3.6}$$

Equation 3.6 is the form first proposed by Fanning [cited by Streeter, 1961]. Hence, the term, f, associated with this equation is known as the Fanning friction factor. A similar development by Darcy and Weisbach [cited by Streeter, 1961] results in the equation

$$H_f = f_D \left(\frac{L v^2}{2 g_c d} \right) \tag{3.7}$$

Equations 3.6 and 3.7 differ only in the numerical coefficient used in the friction factor. The Fanning f is one fourth that of the Darcy f_D.

In any system involving single phase fluid flow in pipes, the flow can be of two kinds, namely laminar and turbulent. In the laminar region, where Reynolds number is below 2000, the friction factor is independent of roughness, and is reasonably approximated by

$$f_D = \frac{64}{Re} \tag{3.8}$$

The turbulent region can be divided into a smooth zone, where the roughness effect is negligible, a rough zone, where flow is independent of viscosity, and a transition zone, where f is a function of Re and pipe roughness, $\frac{\varepsilon}{D}$.

Prandtl [1933] developed the following implicit relation for characterizing the friction factor for turbulent flow in smooth pipes:

$$\frac{1}{\sqrt{f_D}} = -2 \log \left(\frac{2.51}{Re \sqrt{f_D}} \right) \tag{3.9}$$

The constants in the Prandtl equation are based on data developed by Nikuradse [1933]. Von Karman [1934] described the friction factor for turbulent flow in the rough zone as

$$\frac{1}{\sqrt{f_D}} = -2 \log \left(\frac{\varepsilon}{3.7\ D} \right) \tag{3.10}$$

Again, the constants in this equation are also based on the work of Nikuradse [1933].

An expression which more adequately predicts friction factor in the transition region was developed by Colebrook [1938] and combined the Prandtl and von Karman equations to give

$$\frac{1}{\sqrt{f_D}} = -2 \log \left(\frac{2.51}{Re \sqrt{f_D}} + \frac{\varepsilon}{3.7\ D} \right) \tag{3.11}$$

As this equation is non-linear, it must be solved iteratively in order to find a solution for the friction factor.

Moody [1944] developed a graphical representation of friction factor as a function of Reynold's number and pipe roughness. Figure 3.1 illustrates this plot and has served for years as a basis for the evaluation of friction factors. In the computer age, this chart is becoming rapidly obsolete and is being replaced by equations from correlations.

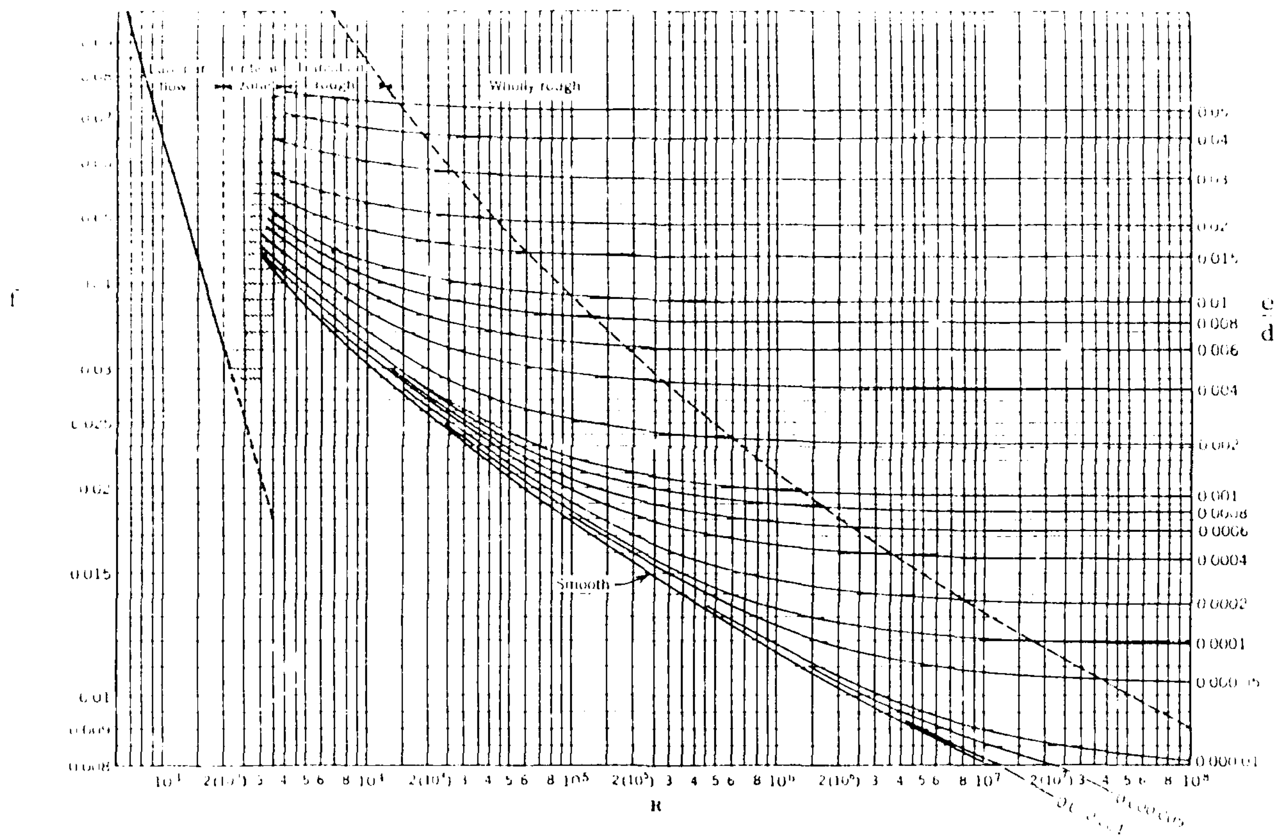

Figure 3.1 Moody friction factor chart.
(Source: Vennard and Street, 1975.)

Many of these correlations are non-linear and must be solved iteratively. However, the solutions to any desired degree of precision is accomplished easily, quickly and cheaply with a digital computer. Wood [1966] developed the first computer-applicable relationship that gave the friction factor explicitly as

$$\sqrt{f_D} = 0.094\,(\frac{\varepsilon}{D})^{0.225} + 0.53\,(\frac{\varepsilon}{D}) + 88\,(\frac{\varepsilon}{D})^{0.4}\,(Re)^{-1.62}\,(\frac{\varepsilon}{D})^{0.134} \tag{3.12}$$

Churchill [1977] developed a more accurate correlating equation that is explicit in form

$$f = \left((\frac{8}{Re})^{12} + \frac{1}{(A + B)^{1.5}} \right)^{\frac{1}{12}} \tag{3.13}$$

Where:

$$A = \left[\left(2.457 \ln \frac{1}{(\frac{7}{Re})^{0.9}} + \frac{0.27\,\varepsilon}{D} \right) \right]^{16}$$

$$B = (\frac{37.530}{Re})^{16}$$

Although Equation 3.13 is valid for all Re and $\frac{\varepsilon}{D}$, a trial- and-error solution is necessary if the pressure drop rather than the flow rate is specified.

Chen [1979] proposed another explicit equation as

$$\frac{1}{\sqrt{f_D}} = -\,2.0 \log \left(\frac{\varepsilon}{3.7065\,D} - \frac{5.0452}{Re} \log \left(\frac{1}{2.8257} (\frac{\varepsilon}{D})^{1.1098} + \frac{5.8506}{Re^{0.8981}} \right) \right) \tag{3.14}$$

Equation 3.14 is superior to those of Wood and Churchill when compared to the iterative solution of Colebrook's equation over the ranges $4000 < Re < 4X10^8$ and $5X10^{-7} < \frac{\varepsilon}{D} < 0.05$.

More recently, Zigrang and Sylvester [1982] presented the following explicit friction factor equation

$$\frac{1}{\sqrt{f_D}} = -2.0 \log \left(\frac{\varepsilon}{3.7\ D} - \frac{5.02}{Re} \log \left(\frac{\varepsilon}{3.7\ D} - \frac{5.02}{Re} \log \left(\frac{\varepsilon}{3.7\ D} + \frac{13}{Re}\right)\right)\right) \qquad (3.15)$$

A numerical comparison of Equations 3.12, 3.13, 3.14, 3.15, and the Moody plot versus the Colebrook equation was performed by Zigrang and Sylvester by using a matrix of 60 test points that combined 10 roughness ratios with six different values of Reynold's numbers. The deviations from the Colebrook equation were computed and are listed in table 3.1.

Each successive attempt at producing a more accurate friction factor equation resulted in a lowering of both the absolute and maximum deviations from the Colebrook equation with the Zigrang and Sylvester giving the best values. Also, this equation is easier to utilize since the friction factor is an explicit function of both the Reynold's number and the pipe roughness.

Automation Techniques

There has been very little information regarding the automation of petroleum pipeline systems published in the literature. This can be expected since most pipeline projects are of a permanent nature. When a company does require new gathering or transmission lines, the project engineer will perform the necessary

Table 3.1

Comparison of explicit approximations to Colebrook's friction factor equation

Investigator	Average Absolute Deviation, %	Maximum Average Deviation, %
Moody Figure 3.1	4.3	16.0
Wood Equation 3.12	2.7	6.0
Churchill Equation 3.13	0.65	3.0
Chen Equation 3.14	0.11	0.32
Zigrang & Sylvester Equation 3.15	0.017	0.11

manual calculations for the construction team. Once in place, the pipeline is used for many years before it is replaced or salvaged. In the military, however, a tactical pipeline system may be moved several times a month if hostile actions have occurred. Therefore, the need for automating the design procedure is quite apparent.

There have been several attempts at programming hand-held calculators to do certain aspects of the pipeline design problem in the past decade. Verma [1980] published the code for a TI-59 programmable calculator that speeds up the calculations for pipe-flow problems that involved horizontal flow of constant density fluids. This program can find either the pressure drop, fluid flow rate, or pipe diameter, given that two of the parameters are known. Scott [1984] wrote a similar program for the HP-41CV calculator that is used for line sizing and to calculate pressure drop due to friction losses for incompressible fluids.

Talwar [1984] developed a program for the TI-59 that determined the economic diameter in pipe and compressor discharge piping. He developed cost factors for various possible fittings as a function of pipe diameter for carbon steel pipe which made it easy to correct for future changes in costs. Also, Fadel [1985] wrote a program for the TI-59 that calculated suction and discharge pressure, and available net positive suction head for a specific pump, taking into account resistance offered by pipes and fittings, flow through equipment, inlet and outlet losses, static head, and pressure at delivery points.

The two most sophisticated pipeline design programs found in the literature were written by Gopalani [1984] and Holmberg [1984]. Gopalani showed how an integrated software package (LOTUS 123) could be utilized for analyzing a complex gathering system with great ease and power. However, this system was

only a few miles long, and each line was at the same elevation. Holmberg developed a pipeline program for the TI-59 that included the initial and final elevations in the design process. This program did not take into account the pump locations or the topography of the land. This approach can only lead to over- or under-design of the pipeline system.

Current Military Pipeline Design

Current design procedures for tactical military pipeline systems include three major areas of interest. They are: characteristics of petroleum fuels; pipeline and pumping station data; and location of pump stations.

Preamble

The fundamental characteristics of fluids must be considered in the design of petroleum pipeline systems, but only the physical properties that affect product storage and movement in pipelines are important. The characteristics of immediate interest are API gravity, viscosity, and their dependency on temperature and pressure.

The petroleum industry uses the API gravity scale almost exclusively to designate gravities of fluid products. It has a one-to-one correspondence with the fluid specific gravity and the two are related by definitions incorporated in the following formula:

$$\text{API gravity} = \frac{141.5}{\text{sp gr}} - 131.5 \qquad (3.16)$$

Fuels that are most often transported by military pipelines are aviation gasoline, motor gasoline, diesel fuel, and jet fuel. Oils, such as kerosene, may occasionally be pumped. Properties of these fuels can be found in Federal specifications. The gravity range of the most common military fuels is given in table 3.2. It is noted that the spread between the heaviest and lightest fuels is about 34° API. With such a wide variation, specific gravity becomes an important factor in the design of military pipelines. The specific throughput of quantities to be pumped on established schedules must be considered, and the heaviest fuel making up 24 percent or more of the total requirement is usually taken as the "design fuel."

Viscosity is a measure of the relative ease or difficulty with which a liquid can be made to flow. The more viscous the liquid is, the greater the internal resistance to flow. Since a viscous liquid resists efforts to move it, absolute viscosity is defined as a measure of the force required to produce flow. The kinematic viscosity of military fuels can be obtained from figure 3.2.

Each of the characteristics discussed above is affected by temperature and pressure. Volume and API gravity increase with temperature while density, specific gravity, and viscosity vary inversely. Because of these effects of temperature, all measurements are corrected to 60°F. This is the standard temperature for both design and operation of military pipeline systems.

In the design of pipelines the elevation of fuels from one level to another and their movement from place to place are governed by the principles of hydraulics. This broad subject includes the pressure and the equilibrium of liquids at rest (hydrostatics), as in a storage tank. It also includes liquids in motion (hydrokinetics), as in an operating pipeline, and forces exerted on liquids by objects in motion (hydrodynamics), as in pumping equipment. All forces which produce

Table 3.2

Specific Gravities of military fuels (60°F)

(based on average API value)

Fuels	API gravities From	To	Average	specific gravity, based on average API value
Avgas:				
115/145	65.8	74.5	70.0	0.7022
100/130	62.6	74.2	68.4	0.7279
91/96	63.7	71.5	67.6	0.7107
MOGAS:				
Regular	58.5	68.9	63.7	0.7250
Premium	58.0	63.0	60.5	0.7370
JP-4	45.0	57.0	51.0	0.7753
Kerosene	39.0	46.0	42.0	0.8156
Diesel:				
50 cetane	34.0	37.0	36.0	0.8448
40 cetane	33.6	37.6	36.0	0.8448

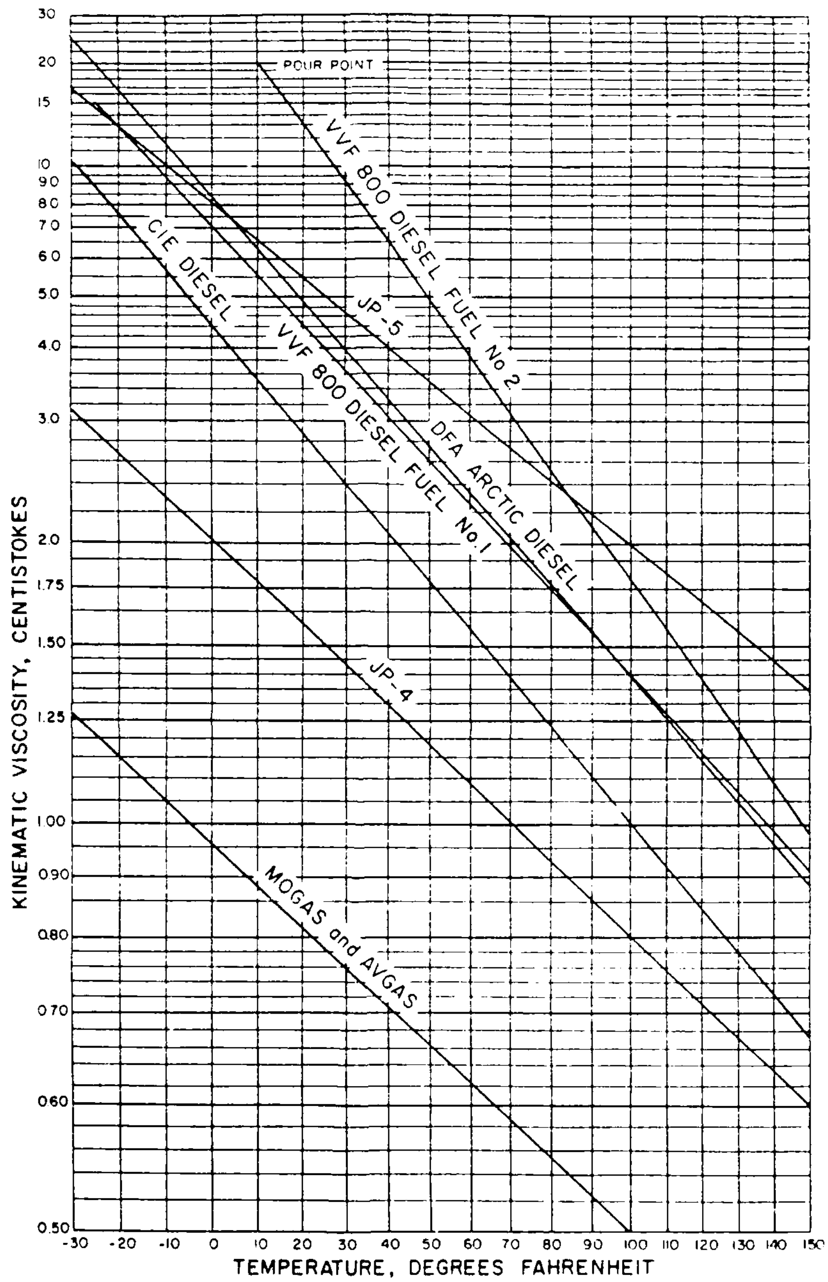

Figure 3.2 Kinematic viscosities for common military fuels.
(Source: Department of the Army, 1986)

pipeline flow and those opposing it can be described or measured in terms of pressure or head. Head in a pipeline is of two kinds: static and dynamic.

Static head is a measure of pressure in liquids at rest and is also a measure of potential energy. It is the vertical height from a given point in a column or body of still liquid to its surface and is usually expressed in feet. The formula for converting pressure to head is

$$\text{Head (feet of water)} = \frac{2.31 \text{ pressure (psi)}}{\text{sp gr}} \tag{3.17}$$

Dynamic head is a measure of pressure in liquids in motion and is also a measure of kinetic energy. The relationship between static head and dynamic head is illustrated in figure 3.3. Static head is measured by the vertical height of liquid in the tank above the ground. When liquid starts to flow down the pipe, it loses static head, but it gains in dynamic head. Potential energy becomes kinetic energy or energy in motion. Dynamic head or velocity is greatest at ground level where the stream changes direction and starts to rise. Dynamic head decreases after that until all velocity is lost. Meanwhile, the stream regains some portion of its initial static head. The difference between initial static head and final static head is the head loss because of friction and change in direction. In other words, dynamic head is the static head required to accelerate the stream to its flowing velocity. It is the elevation to which a pump can push a column of liquid.

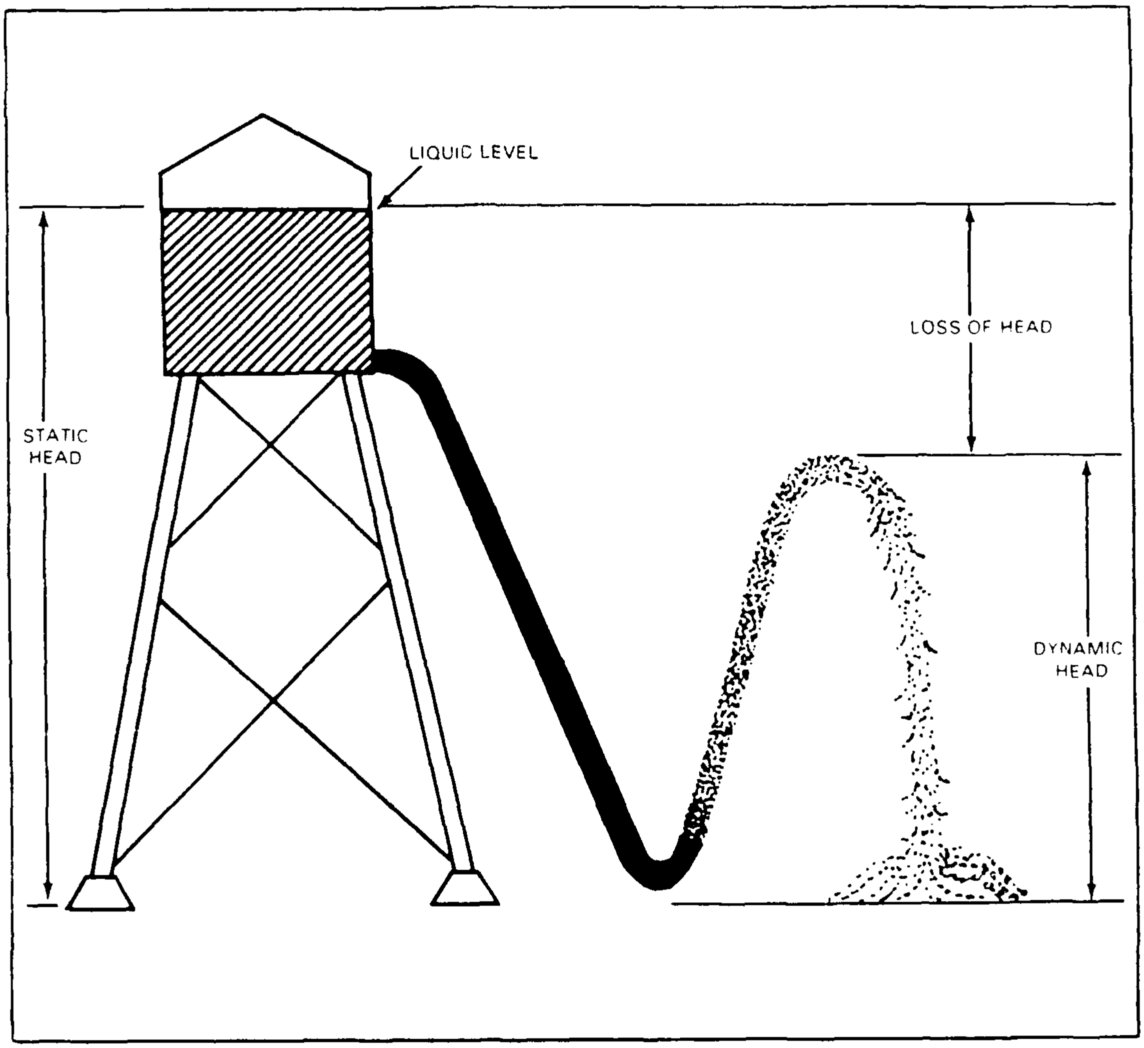

Figure 3.3 Relationship between static head and dynamic head.
(Source: Department of the Army, 1986)

Pipeline and Pumping Station Data

An important consideration in the design of tactical military pipeline systems is the physical properties of both the pipeline and the pumping stations. A knowledge of the operating capabilities of these systems is essential if one wants to optimize the design procedure.

Pipeline capacity, or throughput, is the quantity of fuel pumped per unit time. Generally, it is expressed in barrels per hour (BPH) or gallons per minute (gpm). The normal and emergency capacities of military pipelines, based on 0.725 specific gravity fuel, are given in table 3.3. Normal capacities are always used for pipeline design. The safe working pressures for lightweight tubing are also given in table 3.3. These values are based on the yield point of the pipe material and provide a designed maximum safety factor of 3.0.

There are two sources of "energy loss" within a pipeline system: that resulting from fluid flowing through the pipe and that created by fuel passing by obstructions, such as valves, fittings, and pipelines of smaller diameters. The total friction loss in any section of pipeline is the total of the two "energy losses" and represents the total energy, or head, expended in moving the fuel through a pipeline. In design, it furnishes a parameter on which to base the distances between pump stations on level terrain.

Pipe friction loss arises from the internal friction of the particles of the fluid itself and the resistance to flow at the pipe wall surfaces. The viscosity of a fluid indicates the friction expected from a given flow. For standard military pipe, friction loss is usually obtained from the curves in figure 3.4, for a given velocity of flow or volume of throughput.

Table 3.3

Design capacity of standard military lightweight steel tubing

Outside diameter (in)	Inside diameter (in)	Normal capacity ($\frac{bbl}{hr}$)	Emergency capacity ($\frac{bbl}{hr}$)	Safe working pressure (psi)
4.500	4.350	355	393	600
6.625	6.415	785	1000	600
8.625	8.415	1355	1730	500
12.750	12.481	7150	11400	400

Note: Based on fuel of 0.725 specific gravity.

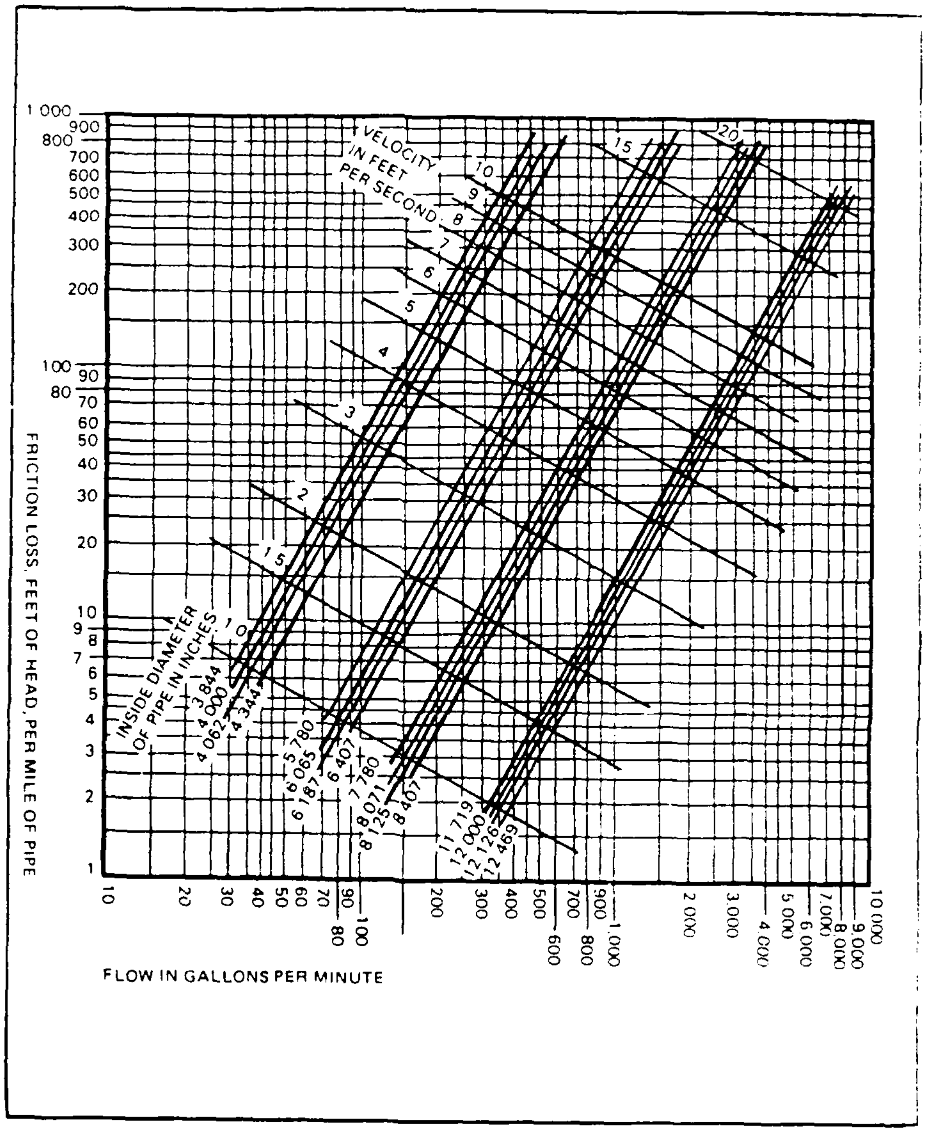

Figure 3.4 Pressure loss due to friction in pipe.
(Source: Department of the Army, 1986)

Friction losses through fittings result from the same surface friction as losses in straight pipe. Such fitting loss is determined by mathematically converting each type fitting into its "equivalent length" of pipe which will have practically the same friction loss. Figure 3.5 lists equivalent pipe lengths for many types of pipe fittings and a full range of inside pipe diameters.

The normal head capacity of a pumping unit is the total head against which it will pump at the most efficient operating point. The head capacity for a particular pump varies according to its design efficiency and is a function of speed (revolutions per minute) versus its rate of discharge (gallons per minute). In other words, the design speed of the pump unit must be considered together with the required head and desired throughput in order to establish maximum efficiency in pipeline design. Optimum head capacities of standard military pipeline pump units are given in table 3.4.

Maximum head capacity of a pumping unit is the total head against which it must pump to provide maximum pipeline capacity. These maximum head capacities for standard military pumping units also are given in table 3.4. It is important to note that maximum head capacities are for emergency operation only and are never used as the basis for design. Pumping stations are not operated at maximum head capacity except during critical tactical emergencies.

Location of Pumping Units

The most important element in the actual design of military pipeline systems is that of pumping station spacing. The spacing is determined by the head loss in the pipe for reasons of friction and elevation when the line is operating at the normal

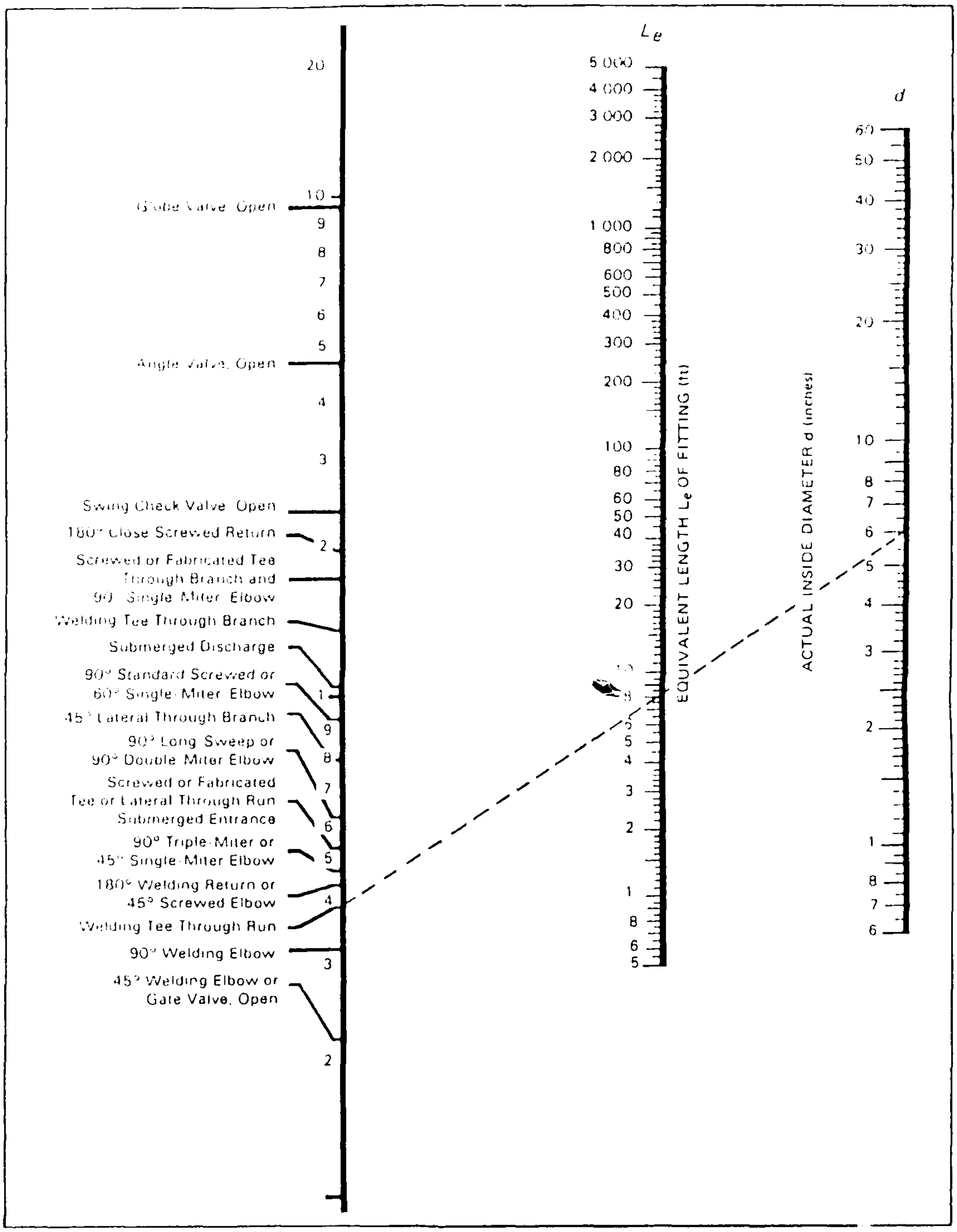

Figure 3.5 Pipe length equivalent to valves and fittings.
(Source: Department of the Army, 1986)

Table 3.4

Operating characteristics of standard pipeline pumping stations[1]

Nominal size of line (in)	Pump units per station		Normal Capacity		Emergency Capacity	
	No.	Type[2]	Head (ft)	Press (psi)	Head (ft)	Press (psi)
4	2	A	1072	336	1321	614
6	4	A	1362	427	2233	700
8	4	B	973	305	1522	477
12	4	B	201	63	217	68

[1] Based on fuel of 0.725 specific gravity and normal operating conditions.

[2] A: four-inch, 4-stage; B: six-inch, 2-stage

capacity for which it is designed.

The current method used by the military to locate pump stations is referred to as modular design. Modular design is a simplified graphical method of locating pumping stations that is essentially the solution of hydraulic calculations by means of two separate graphs. They are: the hydraulic gradient triangle and the profile of the pipeline route.

The hydraulic gradient triangle is a right triangle, constructed on the same scale as the profile. Figure 3.6 illustrates a typical hydraulic gradient triangle. Its altitude (ordinate) represents the available feet of head pressure at the discharge of the design pumping station. Its base (abscissa) represents the distance that the discharge head can move fluid against the friction in the pipeline at the normal design rate of flow on level terrain. The hypotenuse of this triangle is known as the hydraulic gradient. This gradient represents the rate of head loss due to friction for a specific size of pipe, carrying a specific fluid, at a specific rate of flow. If any of these factors change, then a new triangle must be constructed.

The initial pipeline pumping station which receives fuel from the marine terminal tank farm is located as close to the tank farm as safety and convenience of operation permit. Because of its critical position, the station itself and the connecting line to the tank farm require careful planning and design to ensure that sufficient pressure is provided at the pump suction under maximum emergency flow conditions. Where site and job conditions permit, suction pressure at Station No. 1 should be at least 20 psi (64 feet of head of 0.725 specific gravity fuel) under normal conditions. This suction pressure is required to overcome pump entrance losses and to prevent pump vapor lock.

Location of Pumping Station No. 2 by use of the hydraulic gradient triangle

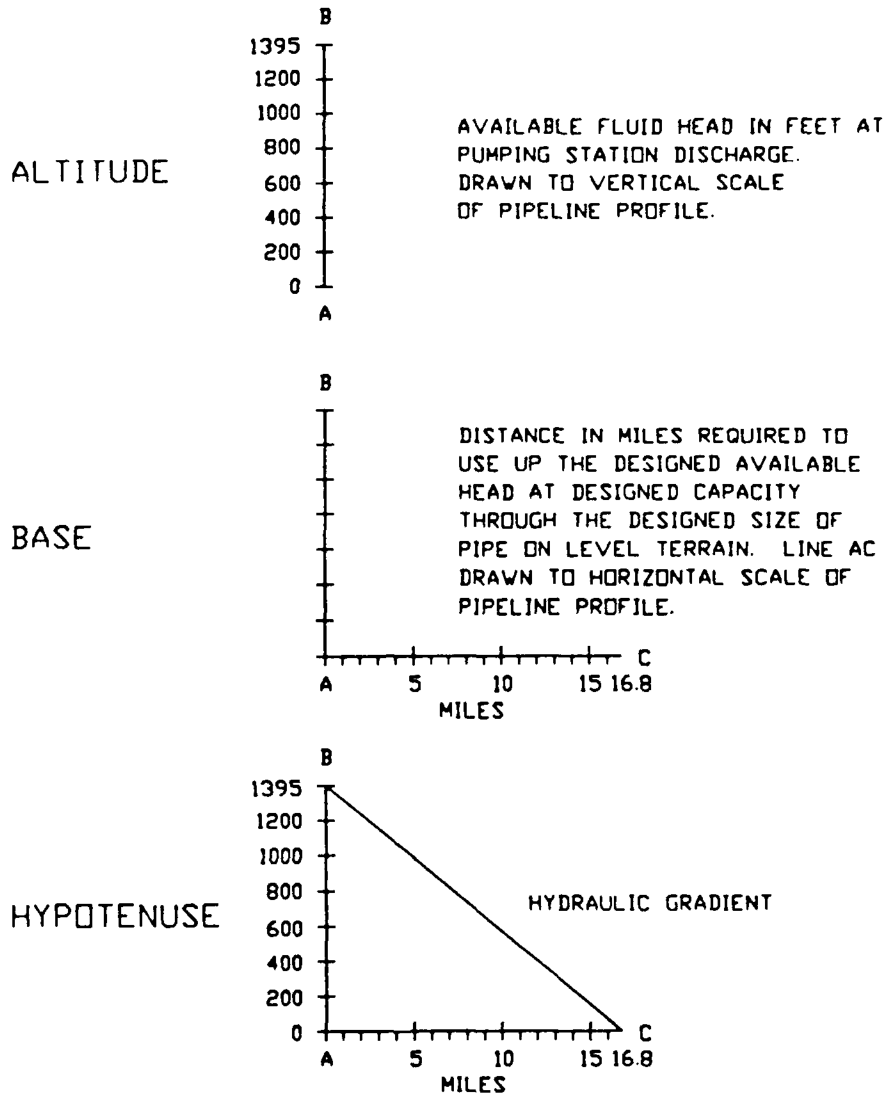

Figure 3.6 Construction of the hydraulic gradient triangle.

depends on the positive suction pressure at Station No. 1. The location of Station No. 2 will maintain the minimum suction pressure which is to be passed along to each succeeding station on the pipeline. This pressure is 20 psi at normal elevations and temperatures.

To locate Station Number 2, place the hydraulic gradient triangle on the pipeline profile with point A (the right angle) at Station No. 1 (see figure 3.7a). The base, AC, of the triangle is positioned parallel to the horizontal baseline of the profile in the direction of flow in the pipeline. The point at which the hypotenuse, BC, intersects the profile is the proper location for Pumping Station No. 2. The pressure at this point will be 20 psi, the same as the suction pressure at Station No. 1. The triangle has measured the pumping distance for only the pressure added by the pumps at Station No. 1, and the suction pressure does not have any bearing. Hence, both stations are hydraulically in balance.

So long as the pipeline profile does not intersect the hypotenuse of the hydraulic gradient triangle, the distance between two successive pumping stations of equal elevation is determined simply by the pressure drop due to pipeline friction. Hills and valleys along the route cancel each other out, and there is no loss of pressure due to changes in elevation. If Pumping Station No. 3 is at the same elevation as Station No. 2, then Station No. 3 will be located where point C of the triangle lies on the pipeline profile, as in figure 3.7b.

If a downstream pumping station is at a higher elevation than the preceding station, it is said to be on an upgrade. Then the total pressure loss between the two stations equals the sum of the separate losses due to friction and to the difference in elevation. Therefore, the downstream upgrade station will be closer to the preceding station than a downstream station at an equal elevation. Figure 3.7c illustrates this

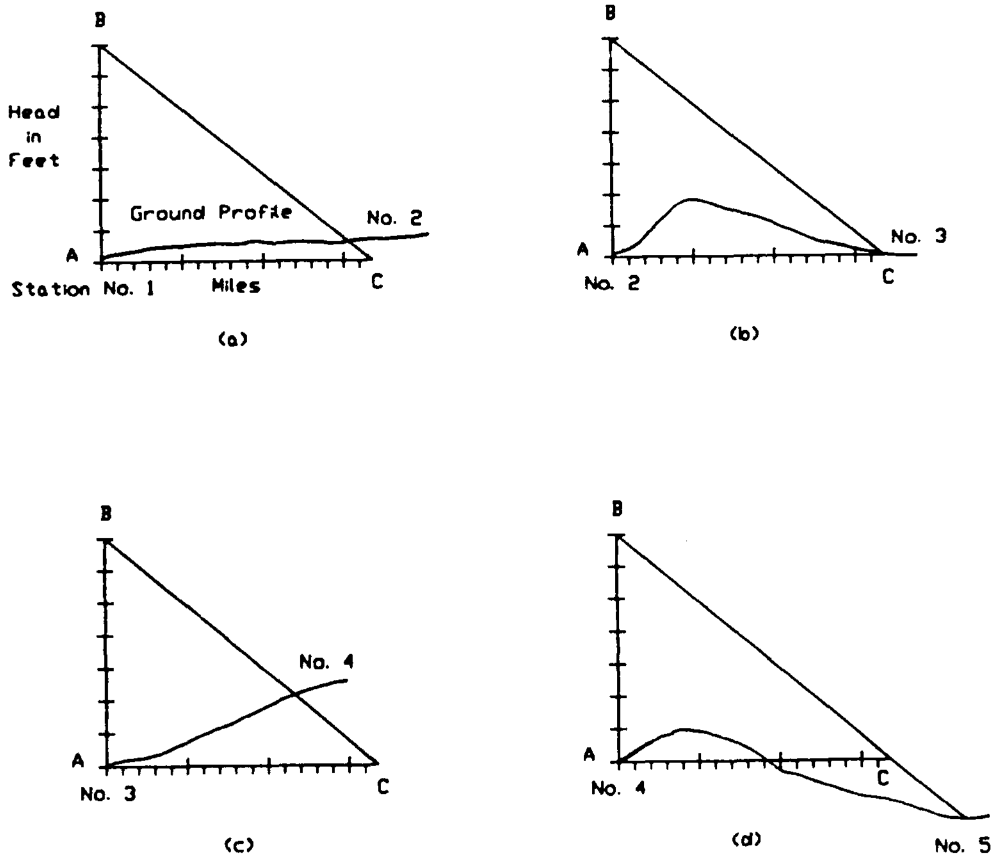

Figure 3.7 Use of the hydraulic gradient triangle to locate pumping stations. (a) Typical pump station spacing. (b) Stations at the same elevation. (c) Downstream pump station at a higher elevation. (d) Downstream pump station at a lower elevation.

case. The first point at which the hypotenuse of the triangle intersects the profile is the appropriate location for Station No. 4.

Should a downstream pumping station site be at a lower elevation than the preceding station, it is said to be downgrade. Here, the pressure loss between stations will amount to the difference between the friction loss in the pipe, and the pressure gain (static head) due to the lower elevation. A downgrade, downstream station, therefore, will be farther from the preceding station than would be the case if both stations were at equal elevation. Figure 3.7d illustrates this case. The point at which the extended hypotenuse, BC, intersects the profile is the proper location for Station No. 5.

By moving the hydraulic gradient from Pump Station No. 1 (the beginning of the pipeline) along the entire length of the proposed pipeline route profile, the total number of pumping stations needed to move the desired product can be calculated. Figure 3.8 illustrates a typical example. Here, five standard 4-inch, four-stage pumping units are needed to move 785 barrels per hour of MOGAS gasoline a distance of 60 miles through 6 5/8-inch steel tubing. If any of the product, pipeline, or pumping station parameters are changed, however, a new hydraulic gradient triangle must be constructed and the entire procedure must be repeated.

New Design Procedures

Currently, the military chooses the heaviest fuel making up 24 percent or more of the total requirement as the design fuel. This method is inefficient because it fails to include the lighter fuels; therefore, the design will call for more pump stations than are necessary. By introducing a weighting scheme that takes into account each

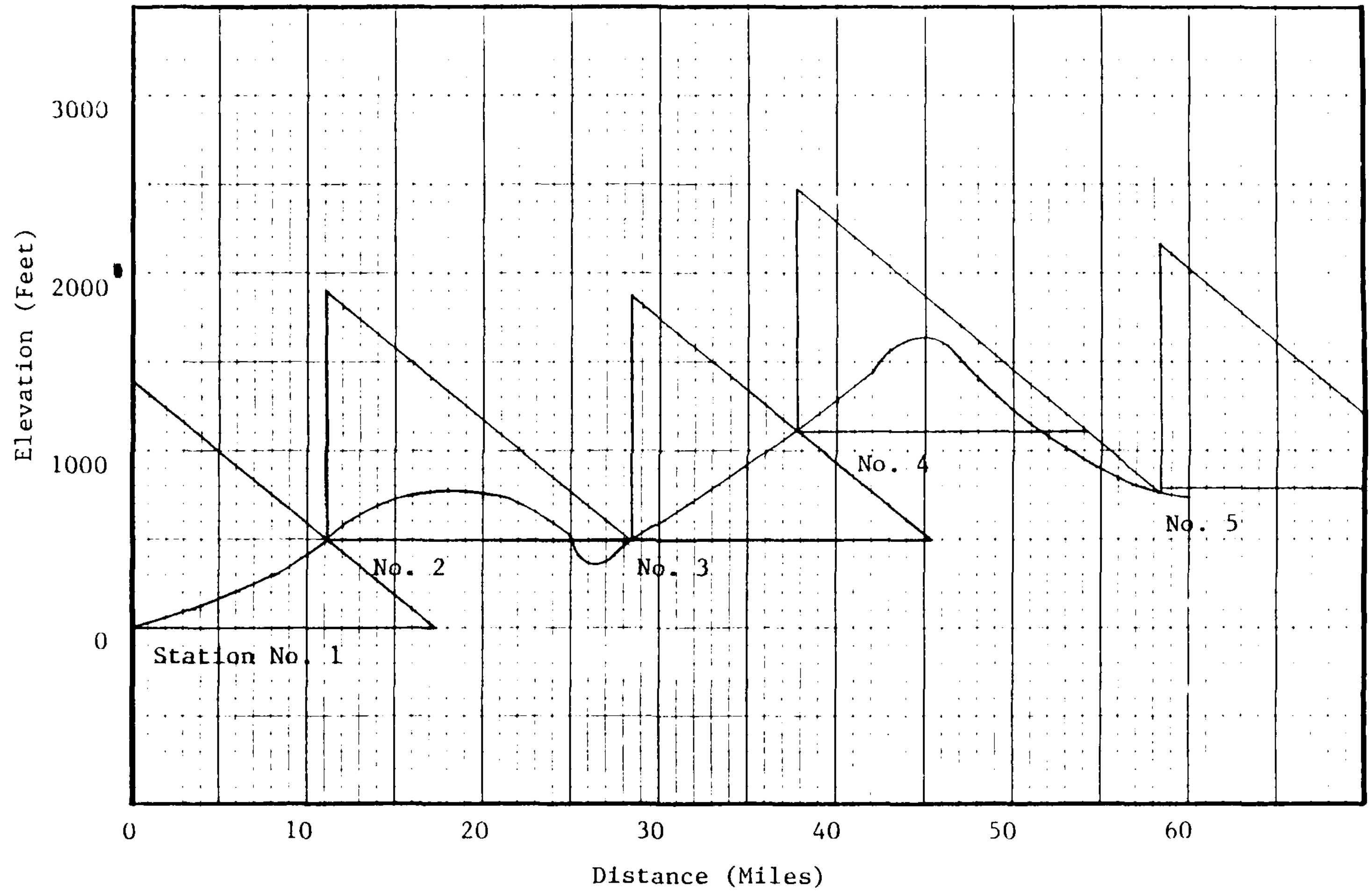

Figure 3.8 Location of pumping stations on the pipeline route profile.

of the fuels in the pipeline, a net savings in pump stations may be incurred.

The first step in choosing a weighting scheme is to analyze the working equation (equation 3.3) for the flow of Newtonian liquids. Equation 3.3 states that the pressure drop is a function of the friction factor and the change in potential energy. This can be represented as

$$\Delta P = f\ (f, L, v, g_c, d, \rho, X) \tag{3.18}$$

The pipeline dimensions are fixed and cannot be altered. Furthermore, the density of each fluid being transported is assumed to be constant and fixed for the given situation.

$$\Delta P = f\ (f) \tag{3.19}$$

The friction factor is left as the logical choice for the weighting scheme. Equation 3.15 will be used to calculate the friction factor. This equation shows that the friction factor is a function of pipe roughness and the Reynold's number and can be represented as

$$f = f\ (Re\ ,\ \frac{\varepsilon}{d}) \tag{3.20}$$

The Reynold's number is chosen as the new design criteria since pipe roughness is constant for military pipes. The Reynold's number is a function of the pipeline diameter, fluid flow rate, density, and viscosity as shown by

$$Re = f\ (d, v, \rho, \mu) \tag{3.21}$$

Since the pipeline dimensions are fixed, the density is assumed constant, and

the change in kinetic energy is assumed zero, equation 3.21 can be reduced to

$$Re = f(\mu) \tag{3.22}$$

Therefore, the new weighting scheme will find a weighted average value for the gravity and kinematic viscosity based on the volume percent of each product in the pipeline at any given time. These volume weighted values will be inserted into the Reynold's number and friction factor equations in order to optimize the design process.

Chapter 4

DEVELOPMENT OF THE COMPUTER PROGRAM

The software that is developed to optimize the design of tactical military pipelines was written in Advanced Basic (IBM DOS) programming language and will run on any IBM-compatible personal computer. The program requires approximately 10K bytes of memory and can be stored on either a 5.25 or 3.5 inch floppy disk. The program does not require any external graphics package and can be executed on both color and monochrome monitors.

This software package was written to be interactive and also user-friendly. By loading data into the input subroutines and printing results from the output subroutines, the user remains isolated from the main program. This enables the user to implement the program quickly without becoming involved with the intricacies of the developed software. The program is composed of three input subroutines, the main program, and two output subroutines.

Input Subroutines

The three input subroutines used in this program are: DATA, TOPO, and PUMP. Each of these was written to be self-explanatory so that a detailed user's guide would not be required to implement the program. All input data are requested in specific units so that the integrity of the hydraulic equations remains unchanged.

Each input subroutine will be discussed below.

Subroutine DATA

The first input subroutine is DATA and is used to load the general characteristics of the pipe and the physical properties of the product into the main program. The name of the pipeline is an alphanumeric field that can be up to ten characters long. The name chosen should be descriptive to distinguish between different design outputs. The length of the pipeline is inputed in miles and is usually a whole number. At this point, the program allows the user to enter the equivalent lengths for any valves or fittings that may be present in the pipeline. The program will add the sum total of the equivalent lengths to the length of the pipeline. The inside diameter of the pipeline is taken from table 3.3. The value entered should be the exact one - not the nominal ID. For example, 6.415 inches should be entered for a 6-inch nominal ID pipe. The last pipe characteristic entered is the absolute roughness. The default value is 0.00015 ft which is standard for all military lightweight steel pipe.

The user will have the option of either using the current military design procedure or the new method based on the volume weighting scheme. The operating temperature of the pipeline is entered in degrees Fahrenheit. The volume percent of each fuel to be transported by the pipeline is also inputed. If the current design option is selected, the program will choose the heaviest fuel making up 24 percent or more of the total requirement as the design fuel. The API gravity and kinematic viscosity of this fuel will be found from table 3.2 and figure 3.2, respectively.

If the new design option is selected, the program will calculate a volume weighted gravity and kinematic viscosity by multiplying the volume percent of each product by their respective gravity or kinematic viscosity. The kinematic viscosities and gravities for the military fuels are stored in this subroutine and accessed through a table look-up algorithm, thus eliminating the need to enter these values each time the program is run.

Finally, the desired flow rate must be entered in barrels per hour. The program will "echo-print" each value entered in subroutine DATA and will give the user the option of changing any of the input data before going on to the next input subroutine.

Subroutine TOPO

The second input subroutine is TOPO and is used to set up the terrain profile for the proposed pipeline route. The user must input elevations taken from topographical maps. These elevations are entered in feet and must be whole numbers. The horizontal distance between each elevation must be identical and is referred to as the "gap." The length of the pipeline and the gap can be entered in fractions of a mile to improve accuracy as long as the ratio length/gap is a whole number. This is necessary because the length/gap quotient is used as an index for several counting loops. For example, the length of the pipeline can be 50.5 miles if the gap is 0.5 miles, thus the quotient is 50.5/0.5 = 101. The first elevation is at the pipeline origin, designated mile marker zero, and the last elevation is at the pipeline endpoint. The program will "echo-print" the elevations and will allow the user to make any changes in this section.

Subroutine PUMP

The final input subroutine is PUMP and is used to identify pump station characteristics, locations, and maximum operating pressures. In this section the user will have the option of either calculating the optimum pump station location or finding the maximum operating pressures for a pipeline with existing pump stations.

The first option finds the pump station location if the maximum operating pressures of each of the available pumps are known. The user must input the number of pump stations, the maximum pressure of each station, and the order in which the pump stations should be used.

The second option will find the maximum operating pressures for an existing pipeline. Here, the user must input the number of pump stations and their locations along the route profile. Again, fractional miles can be used for station locations as long as the ratio (station location / gap) is a whole number. For example, the location for station number 1 can be 9.25 miles if the gap is 0.25 miles, thus the quotient 9.25/0.25 = 37.

Main Program

After entering all the appropriate data into the three input subroutines, the main program starts performing the hydraulic calculations. First, the program calculates the linefill for the proposed pipeline specifications. Next, the program calculates the Reynold's number and determines the appropriate flow type. If the flow is laminar, the friction factor is found using equation 3.8; however, if the flow is turbulent, equation 3.15 is used. The head loss for either flow is found by

inserting the friction factor into equation 3.7.

The program then calculates the head required due to friction and elevation through the use of two loops. The first loop calculates the head if the station locations are the limiting factor; whereas the second loop calculates the head if the station pressures are the limiting factor. For either loop, the main program will step off the route profile and calculate the total head required for each step, ensuring that this requirement does not fall below the minimum net positive suction head or rise above the stipulated maximum allowable pressure. A pump station is located where this calculation can go no further, and the calculation is repeated for the next pump station. The head required at each is stored in the computer memory. Using this value and other input variables, the program calculates the brake horsepower for each station. Conversely, when the positions of the pump stations are known, the program can reverse the calculation and find the pressure requirements for a given Reynold's number.

Finally, the main program tabulates the numerical results and sorts each of the parameters in preparation of the output subroutines.

Output Subroutines

The two output subroutines used in this program are: NUMER and GRAPH. Each one contains the results of the hydraulic design calculations; however, they differ in the manner in which the results are displayed.

Subroutine NUMER

Subroutine NUMER is activated each time the main program is executed. This subroutine will print out in tabular form all the pipe and product information that was listed in Subroutine DATA. The pipeline project name is listed first so that identification of different executions is easily accomplished. Next, this subroutine will print out values of linefill and Reynold's number. Finally, Subroutine NUMER will list the station number, mile point location, head, and brake horsepower for each pump station.

Subroutine GRAPH

After the main program implements subroutine NUMER, the user will have the option of activating subroutine GRAPH. This subroutine graphically depicts the numerical results calculated in the main program. The plot that is generated contains a curve representing the topography of the pipeline route and a curve showing the hydraulic gradient profile. The distance in miles is plotted along the X-axis, and the elevation in feet is plotted along the Y-axis. Subroutine GRAPH gives the field commander a quick, visual picture of where each pump station must be placed.

Chapter 5
DISCUSSION OF RESULTS

Automation

The first objective of this research is to automate the design of tactical military pipeline systems. This objective has been achieved by developing a software package using Advanced Basic (IBM DOS) programming language.

The program was tested by executing the input data from the design example listed in the Department of the Army Field Manual [1969] and comparing the results. This example required 785 barrels per hour of MOGAS to be delivered a distance of 60 miles using 6 5/8-inch steel tubing and 4-inch, four-stage pumping units. The design head capacity of each unit was 1395 feet of head which corresponds to a maximum operating pressure of 438 psi.

Figure 3.8 is the graphical representation of the results listed in the field manual. This pipeline design example was performed manually and took several hours to complete. The results show that five pumping stations were needed to move the product the required distance. Figure 5.1 shows the numerical results generated by the program and also shows that five pumping units are required. The program required only a few seconds to execute, however, and gave the exact location and required horsepower for each pump station. Figure 5.2 graphically depicts the same results and compares favorably with figure 3.8.

The biggest advantage in automating the pipeline design procedure is the ability to quickly observe how a change in any of the design parameters affects the

NAME OF PIPELINE PROJECT	TEST	
LENGTH OF PIPELINE	60	MILES
INSIDE DIAMETER OF PIPE	6.415	INCHES
ROUGHNESS OF PIPE	.00015	FEET
API GRAVITY OF PRODUCT	63.75	DEGREES API
VISCOSITY OF PRODUCT	.62	CENTISTOKES
DESIRED FLOW RATE	785	BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS	12663.26	BARRELS
THE REYNOLDS NUMBER IS	436582.7	

PUMP STATION #	HEAD (FT)	MILE PT.	BRAKE-HP
1	1189.771	0	140.761
2	983.8168	10	116.3947
3	981.6793	18	116.1418
4	1203.817	32	142.4228
5	919.542	40	108.7904

Figure 5.1 Numerical output for design project Test.

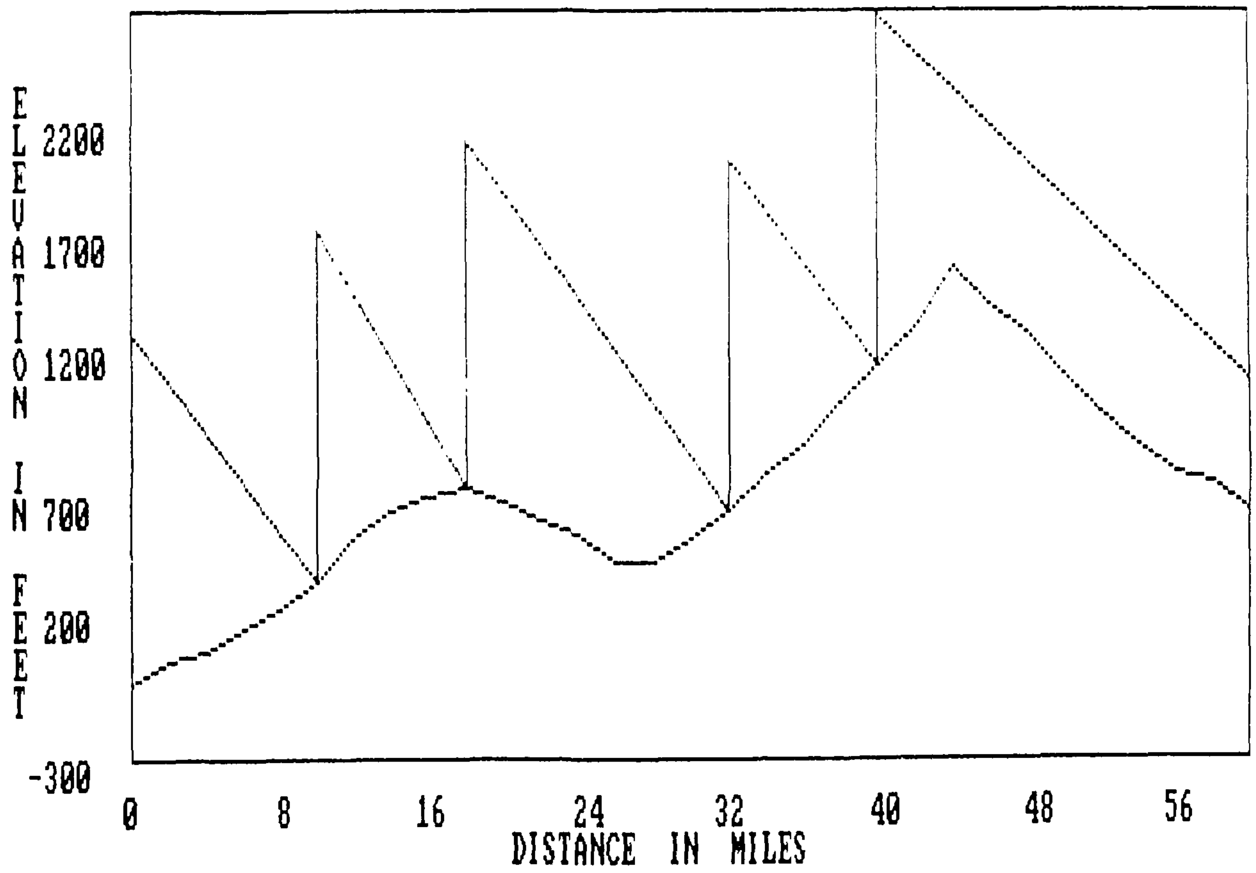

Figure 5.2 Graphical output for design project Test.

station locations. Typically, after the proper hydraulic locations of the pumping stations have been plotted on the profile of the pipeline, a site "reconnaissance" is made and the locations are plotted on topographic maps. The pumping station locations selected by the design procedure may be unsuitable for a number of reasons. The locations may be inaccessible, difficult to camouflage, have poor vapor drainage or involve other impossible terrain conditions. Then the pumping station must be shifted upstream or downstream for a reasonable distance to a better site on the pipeline. By varying the design parameters, the user can overcome any terrain limitation.

By implementing the second option, the user can analyze existing pipelines in which the pump station locations are known. This option would be used in more industrialized theaters of operation where various pipelines are already in place. The maximum operating pressures for each of the existing pump stations could be determined for any of the required products to be transported.

Optimization

The second objective of this research is to optimize the design of tactical military pipeline systems. This objective was achieved by introducing a weighting scheme for the pipeline products into the hydraulic equations.

The weighting scheme was tested using a proposed pipeline with the following characteristics: 100 miles long, 6 5/8-inch diameter steel tubing with an absolute roughness of 0.00015 feet, 785 barrels per hour delivery rate, four-inch, four-stage pumping units, and a typical terrain profile. The products being transported were MOGAS, diesel, and JP-4. The volume percent of each of these fuels for five

different test cases are found in table 5.1. It should be noted that the terrain profile was the same for each case.

Each of these test cases represents a support unit requirement. They are as follows: test case A would supply the fuel requirements for a mechanized division; B would supply an air field; C would supply two air fields and a mechanized division; D would supply two mechanized divisions and an air field; and, E would supply a headquarters division.

Cases A, C, D, and E would each use diesel as the design fuel according to the military design criteria, whereas, case B would use JP-4. First, cases A and B were run through the program without the weighting scheme and the results are shown in figures 5.3 and 5.4, respectively. Next, all five test cases were run through the program using the volume weighting technique and those results are found in figures 5.5 through 5.9, respectively. The first letter of each name corresponds to the particular test case. The middle three-digit number represents the length of the pipeline. The final one-digit number lists the design criteria, with one being the military method and two being the weighting scheme.

The results are summarized in table 5.2. Each of the first four weighted test cases required less pump stations than case A-100-1, with the station savings ranging from 7.7 to 23.1%. As the volume percent of the lighter fuels (i.e., MOGAS and JP-4) increased, the net savings in pump stations also increased. The weighted test case for JP-4 did not show a savings in pump stations when compared with B-100-1. This was expected since any reduction in viscosity from the lighter MOGAS (5%) was offset by the increase caused by the heavier diesel (5%).

The biggest advantage in optimizing the pipeline design procedure is the net savings of pump stations that each tactical refueling process requires. By using the

Table 5.1

Product ranges used in testing the weighting scheme

	Test Case Name				
Product	A	B	C	D	E
MOGAS	10%	5%	10%	10%	50%
JP-4	0%	90%	60%	30%	0%
Diesel	90%	5%	30%	60%	50%

Note: Each table entry represents the volume percent that the product is in the pipeline at any given time.

```
NAME OF PIPELINE PROJECT        A-100-1
LENGTH OF PIPELINE               100   MILES
INSIDE DIAMETER OF PIPE          6.415   INCHES
ROUGHNESS OF PIPE                .00015   FEET
API GRAVITY OF PRODUCT           36   DEGREES API
VISCOSITY OF PRODUCT             3.9   CENTISTOKES
DESIRED FLOW RATE                785   BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS        21105.43   BARRELS
THE REYNOLDS NUMBER IS                   69405.44
```

PUMP STATION #	HEAD (FT)	MILE PT.	BRAKE-HP
1	813.2933	0	112.1611
2	953.2933	6	131.4685
3	793.2933	12	109.4029
4	946.5867	18	130.5436
5	973.2933	30	134.2267
6	1053.293	36	145.2595
7	751.0177	42	103.5727
8	871.0177	56	120.1219
9	793.2933	70	109.4029
10	768.8622	76	106.0336
11	757.7245	80	104.4976
12	788.8622	88	108.7918
13	97.72442	92	13.47716

Figure 5.3 Numerical output for design project A-100-1.

```
NAME OF PIPELINE PROJECT        B-100-1
LENGTH OF PIPELINE              100   MILES
INSIDE DIAMETER OF PIPE         6.415   INCHES
ROUGHNESS OF PIPE               .00015   FEET
API GRAVITY OF PRODUCT          51   DEGREES API
VISCOSITY OF PRODUCT            1.1   CENTISTOKES
DESIRED FLOW RATE               785   BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS       21105.43   BARRELS
THE REYNOLDS NUMBER IS                  246073.8
```

PUMP STATION #	HEAD (FT)	MILE PT.	BRAKE-HP
1	956.0812	0	121.0158
2	902.0609	8	114.1782
3	898.1422	14	113.6821
4	862.0609	28	109.1152
5	942.0609	34	119.2411
6	1046.183	40	132.4203
7	1106.183	58	140.0148
8	1030.102	76	130.3849
9	1002.061	86	126.8356
10	0	92	0

Figure 5.4 Numerical output for design project B-100-1.

NAME OF PIPELINE PROJECT	A-100-2
LENGTH OF PIPELINE	100 MILES
INSIDE DIAMETER OF PIPE	6.415 INCHES
ROUGHNESS OF PIPE	.00015 FEET
API GRAVITY OF PRODUCT	38.7 DEGREES API
VISCOSITY OF PRODUCT	3.572 CENTISTOKES
DESIRED FLOW RATE	785 BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS 21105.43 BARRELS
THE REYNOLDS NUMBER IS 75778.62

PUMP STATION #	HEAD (FT)	MILE PT.	BRAKE-HP
1	804.9744	0	109.2528
2	944.9744	6	128.2539
3	784.9744	12	106.5384
4	929.9488	18	126.2146
5	964.9744	30	130.9683
6	1044.974	36	141.8261
7	973.2649	42	132.0935
8	811.6068	58	110.153
9	944.9744	72	128.2539
10	806.6325	78	109.4778
11	1084.974	86	147.255
12	86.63244	92	11.75794

Figure 5.5 Numerical output for design project A-100-2.

NAME OF PIPELINE PROJECT B-100-2
LENGTH OF PIPELINE 100 MILES
INSIDE DIAMETER OF PIPE 6.415 INCHES
ROUGHNESS OF PIPE .00015 FEET
API GRAVITY OF PRODUCT 50.885 DEGREES API
VISCOSITY OF PRODUCT 1.216 CENTISTOKES
DESIRED FLOW RATE 785 BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS 21105.43 BARRELS
THE REYNOLDS NUMBER IS 222599.7

PUMP STATION #	HEAD (FT	MILE PT.	BRAKE-HP
1	963.0093	0	121.9695
2	907.257	8	114.9083
3	910.2664	14	115.2894
4	867.257	28	109.8421
5	947.257	34	119.9744
6	1061.771	40	134.4782
7	1121.771	58	142.0774
8	1038.762	76	131.5639
9	1007.257	86	127.5737
10	0	92	0

Figure 5.6 Numerical output for design project B-100-2.

NAME OF PIPELINE PROJECT	C-100-2
LENGTH OF PIPELINE	100 MILES
INSIDE DIAMETER OF PIPE	6.415 INCHES
ROUGHNESS OF PIPE	.00015 FEET
API GRAVITY OF PRODUCT	47.775 DEGREES API
VISCOSITY OF PRODUCT	1.892 CENTISTOKES
DESIRED FLOW RATE	785 BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS 21105.43 BARRELS
THE REYNOLDS NUMBER IS 143066.2

PUMP STATION #	HEAD (FT)	MILE PT.	BRAKE-HP
1	998.7302	0	128.6881
2	934.0476	8	120.3537
3	972.7778	14	125.3441
4	894.0476	28	115.1996
5	974.0476	34	125.5077
6	872.7778	40	112.4589
7	962.1428	54	123.9738
8	894.0476	72	115.1996
9	1023.413	78	131.8685
10	728.0952	88	93.81633

Figure 5.7 Numerical output for design project C-100-2.

```
NAME OF PIPELINE PROJECT          D-100-2
LENGTH OF PIPELINE                 100    MILES
INSIDE DIAMETER OF PIPE            6.415   INCHES
ROUGHNESS OF PIPE                  .00015   FEET
API GRAVITY OF PRODUCT             43.275   DEGREES API
VISCOSITY OF PRODUCT               2.732   CENTISTOKES
DESIRED FLOW RATE                  785    BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS        21105.43   BARRELS
THE REYNOLDS NUMBER IS                   99078.05
```

PUMP STATION #	HEAD /FT	MILE PT.	BRAKE-HP
1	1035.428	0	136.8518
2	961.5707	8	127.0902
3	809.2646	14	106.9626
4	835.4276	24	110.4179
5	981.5707	32	129.7335
6	1101.571	38	145.5939
7	886.2827	44	117.1394
8	895.4276	68	118.3481
9	801.5707	76	105.9431
10	1055.428	82	139.4952
11	389.2846	90	51.45148

Figure 5.8 Numerical output for design project D-100-2.

```
NAME OF PIPELINE PROJECT       E-100-2
LENGTH OF PIPELINE              100    MILES
INSIDE DIAMETER OF PIPE         6.415    INCHES
ROUGHNESS OF PIPE               .00015    FEET
API GRAVITY OF PRODUCT          49.85    DEGREES API
VISCOSITY OF PRODUCT            2.26   CENTISTOKES
DESIRED FLOW RATE               785   BBLS/HOUR

THE LINEFILL FOR THIS PIPELINE IS       21105.43    BARRELS
THE REYNOLDS NUMBER IS                  119770.5
```

PUMP STATION #	HEAD (FT)	MILE PT.	BRAKE-HP
1	1015.642	0	129.3699
2	946.7316	8	120.5922
3	843.4631	14	107.4382
4	1065.642	26	135.7387
5	986.7316	34	125.6873
6	844.5526	40	107.5769
7	869.1052	50	110.7044
8	1095.642	70	139.56
9	1044.553	78	133.0524
10	753.4631	88	95.97419

Figure 5.9 Numerical output for design project E-100-2.

Table 5.2

Comparison of the current design approach with the new design approach.

Name	Number of Pump Stations Required Current Design	 New Design	Percent Savings
A-100-2	13	12	7.7
B-100-2	9	9	0
C-100-2	13	10	23.1
D-100-2	13	11	15.4
E-100-2	13	10	23.1

developed weighting scheme, the field commander will be better able to allocate his scarce pipeline components, and will ultimately be able to deliver more fuel throughout a wider area of the battle zone.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A software package has been developed to automate and optimize the design parameters in tactical military petroleum pipeline systems. The software generated is written in Advanced Basic (IBM DOS) programming ianguage and made to run on an IBM-compatible personal computer.

The program incorporates the most current hydraulic design equations and was written to be interactive and user-friendly. The user has the option of either finding the optimum pump station locations for a proposed pipeline or calculating the maximum operating pressures for an existing pipeline. The program allows the user to quickly observe how a change in any of the design parameters affects the station locations.

The design process was optimized by developing and implementing a weighting scheme based on the volume percent of each fuel in the pipeline at any given time. The scheme calculates a volume weighted average for the gravity and kinematic viscosity and used these values in the Reynold's number and friction factor equations. The weighting scheme was tested and compared with current military design examples and showed pump station savings ranging from 7.7 to 23.1%. As the volume percent of the lighter fuels in the pipeline increased, the net savings of pump stations also increased. These savings in pump stations allow the

field engineer to allocate his battlefield resources in a more efficient and frugal manner.

Recommendations

The next logical step in the pipeline design process would be to investigate other weighting and mixing rules and see how they compare with the method developed in this research. A complete parametric study could be performed to determine the best weighting technique for each design problem encountered in either the commercial oil production fields or the military battlefield.

Future research should be directed at improving the pipeline design process by utilizing the fundamental hydrodynamic approach. Such research, combined with intricate mixing formulas, may yield an even greater savings in pipeline components.

Another important element in future research in this problem is the coupling of phase behavior packages with the design equations thus making fluid property prediction more accurate. It is expected that this could help out considerably with reducing the cost of pump stations.

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